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# Recovery Efficiency Aspects of Horizontal Well Drilling in Devonian Shale

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## ABSTRACT

This study is part of the Department of Energy's Eastern Gas Shales research whose primary objective is to increase the gas reserves for the Devonian shales in the Appalachian, Illinois, and Michigan Basins. The study simulated the effect of using horizontal wells to increase the recovery efficiency of shale gas from two specific sites: Wayne County, West Virginia, where vertical well gas production has been historically high and no permeability anisotropy is thought to exist, and Meigs County, Ohio, an area with a history of moderate gas production and a calculated permeability anisotropy of approximately 8:1.

In this study, a three-dimensional, dual-porosity reservoir simulator was used to characterize the study areas after sensitivity analyses were made to determine those parameters significant in determining gas production profiles. Once the study areas were characterized, the 20-year production profile for a 2,000-foot (610-meter) horizontal well was simulated for three well locations in Wayne County and one location in Meigs County. The performances for several vertical wells were also simulated and compared with those for their corresponding horizontal wells in Wayne County. Results of the simulation showed that a horizontal well could produce seven to ten times more gas than a vertical well placed at the same location for the Wayne County site. In the Meigs County area, the study showed that permeability anisotropy is an important factor in determining the orientation that a horizontal well should be drilled. Furthermore, the study concluded that horizontal wells are more efficient than vertical wells in producing Devonian shale gas from a fixed volume of rock.

## INTRODUCTION

The U.S. Department of Energy (DOE) has been conducting research to determine economical ways of producing natural gas from Devonian shale for over 10 years. In support of this research, the United States Geological Survey (USGS) estimated the in-place gas of the Appalachian Basin Devonian shales to be 577-1,100 Tcf (1) ($1.6 \times 10^{13}$-$3.1 \times 10^{13} m^3$) with 85-160 Tcf ($2.4 \times 10^{12}$-$4.5 \times 10^{12} m^3$) located in areas of historical shale gas production. As of 1976, only about 3 Tcf ($8.5 \times 10^{10} m^3$) of this large resource had been produced by about 10,000 vertical wells (2). Gas production from the shales has not increased substantially since this time although the number of shale wells is now in excess of 12,000.

Earlier efforts by DOE (3) showed that only 10-20 percent of the available shale gas was being produced with stimulated vertical wells. Analysis of shale gas production mechanisms indicated that an increase in the amount of surface area connected to the borehole by fractures could cause more of the adsorbed gas to be released and produced over the entire life of the well. This potential increase in recovery efficiency was thought to be achievable using a directionally drilled horizontal well to cross natural fractures orthogonally. Afterwards the horizontal well would be stimulated to increase the surface area in contact with the borehole. This study was undertaken to investigate the feasibility of using horizontal wells in Devonian shales.

## CANDIDATE SITES FOR HORIZONTAL WELLS

Two areas having different geologic properties were selected from a site selection screening survey that was completed in August 1986. More details on the Wayne County horizontal well site selection activity are described in SPE 16410 (SPE/DOE Low Permeability Reservoirs Symposium, Denver, Colorado, May 1987) (4). Within the geologically most favorable area, reservoir simulation was used to determine where in the Wayne County area (Figure 1, Wilsondale and Webb Quadrangles) a 2,000-foot (610-meter) horizontal shale well should be drilled to measure the effect of horizontal drilling on recovery efficiency. Results from this simulation study showed that horizontal wells have high potential for producing large

References and illustrations at end of paper.

volumes of natural gas and could produce several times the production from a vertical well placed at the same location. This concept is currently being tested at location WHW2 in Figure 2.

The Meigs County site (Figure 3) was investigated for comparison because the geology is less complex and because a large amount of reservoir data was available from an extensive field test conducted in 1981 (5). In this area the reservoir was known to have a permeability anisotropy ratio of 8:1. DOE was interested in knowing how anisotropy affects the performance of a horizontal well that might be placed in this area. Reservoir data from DOE's earlier field test in this area provided the baseline information for the simulation. The field test basically consisted of the drilling of two offsets to an existing base well, the extraction and analysis of cores, and a series of production drawdown/buildup interference tests. Accordingly, measurements were available on the following: (1) flow characteristics of gas in fractured shale, (2) orientation and distribution of natural fractures, (3) storage and release mechanisms of gas from the shale, and (4) directional gas flow and its impact on production practices.

## SINGLE WELL ANALYSIS

The radial flow option of a three-dimensional, dual-porosity reservoir simulator (6,7) was used to history match 25 individual wells in Wayne County by varying fracture permeability, $k_f$, and thickness, h, which had the most effect on model output as determined from sensitivity analyses. The way the model describes the storage and flow mechanisms of gas in shale is depicted in Figure 4. The 25 wells were selected from an original set of 38 in a 16 $mi^2$ (41 $km^2$) area based on the criteria that a well had at least 5 years of production history and was producing exclusively from shale. Several model input parameters were held constant for the history matching exercise and their values are listed in Table 1. These values were obtained from a previous DOE study (8). The individual history matching was necessary to obtain a base set of values for the reservoir properties within the study area which would account for variations in the productive performance throughout the area. The resultant data sets provided the base case for beginning three-dimensional, multiwell simulations. The range of values determined by the individual well history are listed in Table 2 for the Wayne County site.

Individual well history matching was performed for 15 Meigs County wells in a 7.5 $mi^2$ (19 $km^2$) area in order to characterize this area. The fixed parameters were again taken from a previous DOE study (9) and are listed in Table 3. The most significant gas production controlling parameters determined by history matching are listed in Table 4. Again the data obtained from the individual matches provided the base case for beginning three-dimensional, multiwell simulation in Meigs County.

Since the primary analysis tool used in this study was a dual-porosity reservoir simulator, it is important to understand how the model works and what is involved in history matching. The dual-porosity model simulates and predicts production performance from a naturally fractured reservoir. It depicts a dual-porosity system in which gas is stored in the shale matrix (less permeable portion of the shale) and subsequently released into the natural fracture network, which provides a transport mechanism for the gas when linked to the borehole. History matching consists of adjusting input parameters for a model until the simulated well or field performance is close to the actual historical performance.

## MULTIWELL ANALYSIS

### Effect of Site on Performance

For the Wayne County study area, contour maps were determined for current rock pressure, $k_f$, h, and $k_f \cdot h$ after minor adjustments were made in the $k_f$ and h profiles from individual well history matching so the production performance for wells in a reduced area matched both individually and collectively. The original 16 $mi^2$ (41 $km^2$) area was reduced to 2 $mi^2$ (5 $km^2$) containing seven active vertical wells in order to expedite computer turnaround time. A three-dimensional reservoir simulator was used for this study. Using this model, the performance of a vertical or horizontal well was simulated for various sites in the smaller study area. (See Figure 2.) Also, shown in Figure 2 are the locations of the seven actual vertical wells, W1-W7, in the reduced study area along with the sites of three 2,000-foot (610-meter) horizontal wells whose performances were simulated. Table 5 shows the completion dates for the seven wells used in the analysis along with their cumulative production values as of the end of 1985.

The simulated performances of three 2,000-foot (610-meter) horizontal wells were determined for the locations WHW1, WHW2, and WHW3 (Figure 2) using the following procedure. First vertical well production was simulated (for production starting in 1932) and then subsequent vertical wells were added at appropriate times and the entire seven well set was simulated until 1985. At this point a horizontal well was placed on line at site WHW1 and its performance was simulated until 2005 (20 years). The performance of a vertical well located at the "best" site (highest $k_f \cdot h$ value) was also simulated for the same 20-year period. The amount of gas stolen from the seven actual vertical wells was calculated and is designated as interference in this paper. The horizontal wells performance was determined for both stimulated and unstimulated cases. Then the horizontal well was simulated for other locations (WHW2 and WHW3). Data analysis showed that a wide variation in production by a 2,000-foot (610-meter) horizontal well exists at the Wayne County site; for example, the production was 149 MMcf ($4.2 \times 10^6 m^3$) for WHW3 and 820 MMcf ($2.3 \times 10^7 m^3$) for WHW1. This means that WHW3 was probably losing its gas to the vertical well, W4, which is one of the best producing vertical wells in the area. WHW2 showed the least interference with the existing reservoir with only 15 MMcf ($4.2 \times 10^5 m^3$) over the 20-year period. WHW2 is the site of the METC horizontal well experiment. Another interesting aspect of the simulation was the improvement ratio of a horizontal well over a vertical well at the same site. The ratios ranged from 7:1 for WHW1 and WHW2 to 10:1 for WHW3. This analysis was only done for unstimulated wells. These observations are summarized in Table 6. All of the simulations described for the Wayne County site used a 60 x 70 x 3 grid overlay and the simulations were conducted on a VAX 8650.

### Effect of Horizontal Well on Drainage Efficiency

DOE engineers were interested in the comparative drainage efficiency of a horizontal well. In order to answer this question, simulation runs were made for two vertical wells placed at the end points of the 2,000-foot (610-meter) horizontal well WHW2. This is equivalent to 72-acre (2.9 x $10^{5}m^{2}$) well spacing (not uncommon for vertical shale wells). The drainage area for these two vertical wells was compared to that of the horizontal well WHW2. Their drainage areas were almost identical as shown in Figure 5. However, the 20-year cumulative production values showed that the horizontal well was three times more efficient than the two vertical wells (unstimulated wells) for producing gas from a fixed volume of rock. This analysis shows the high potential of horizontal wells to produce gas that is currently being left in the ground with vertical wells in shale reservoirs.

### Effect of Horizontal Wells on Field Development Strategy

The next simulation was performed to determine how effective a 2,000-foot (610-meter) horizontal well would be in developing a virgin reservoir. All seven vertical wells were assumed to produce from 1932 until the end of 1985 and their cumulative production was compared to that of a 2,000-foot (610-meter) stimulated horizontal well WHW2. The seven vertical wells showed a cumulative production of 4.56 Bcf (1.3 x $10^{8}m^{3}$) while the horizontal well showed 4.43 Bcf (1.25 x $10^{8}m^{3}$) for the same period. This indicates that horizontal wells provide a viable development option for virgin shale areas as well as for infill drilling in existing reservoirs.

### Effect of Anisotropy on Horizontal Well Orientation

For the Meigs County site, the study area was reduced from 15 wells in a 7.5 $mi^{2}$ (19 $km^{2}$) area to 5 wells in a 1.6 $mi^{2}$ (4 $km^{2}$) area (Figure 6) and the same simulation procedures were followed for this reduced site as for the Wayne County site using a 65 x 60 x 3 grid overlay. Information for the vertical wells in the Meigs County reduced study area is shown in Table 7. The Meigs County study was conducted primarily to determine the effect of permeability anisotropy on horizontal well placement. The Meigs County site was known to have a permeability anisotropy of 8:1 and the Wayne County site was thought to have no anisotropy. In order to determine this effect, a 2,000-foot (610-meter) horizontal well, MHW1, was placed perpendicular to the horizontal borehole at MHW. The 20-year cumulative production values for these two wells were significantly different; that is, the simulated production was 486 MMcf (1.4 x $10^{7}m^{3}$) when the well, MHW, was oriented normal to the preferred flow direction and 205 MMcf (5.8 x $10^{6}m^{3}$) when the well, MHW1, orientation was parallel to the preferred flow direction. This 2.4:1 ratio shows that the effect of permeability anisotropy on well location is significant.

## ECONOMIC ANALYSIS

An economic analysis was performed for the stimulated horizontal well (WHW2) in Wayne County. The objective of the analysis was to determine what the drilling and completion costs would have to be in order to have an after tax well payout in three and five years for gas prices of \$2.00/Mcf and \$3.50/Mcf. The analysis showed that a gas price of \$3.50/Mcf was required to pay out an investment of not more than \$687,000 in five years at 20 percent rate-of-return. The data were generated using a discounted-cash-flow model developed specifically for Devonian shale wells and are summarized in Table 8. An additional analysis was also undertaken to determine if two vertical wells could compete with a 2,000-foot (610-meter) horizontal well. The horizontal well was predicted to have a shorter payout time and higher after tax profits than two vertical wells at any gas price. These data are summarized in Table 9. Similarly, an analysis was conducted for a stimulated well at site MHW in Meigs County. The economics were not as favorable for a 2,000-foot (610-meter) horizontal well in Meigs County since an investment of not more than \$255,000 would be required to payout a well in five years at a gas price of \$3.50/Mcf. This information is summarized in Table 10. Again, a horizontal well was predicted to have a shorter payout time and higher after tax profits than two vertical wells in Meigs County for any gas price. The data are summarized in Table 11.

## CONCLUSIONS

The following conclusions are supported by the analysis presented in this paper:

- Horizontal wells are more effective in draining gas from a comparable volume of rock than are vertical wells.
- To maximize production, horizontal wells need to be drilled orthogonal to the perferred flow direction associated with the natural fracture system.
- Horizontal wells are more economical than vertical wells for developing an existing reservoir through infill drilling or for developing a virgin reservoir.
- Production from horizontal wells, when used for infill drilling, varies with rock pressure, productive capacity ($k_f \cdot h$), wellbore orientation with respect to the natural fracture system, and interference from existing wells in the reservoir.

## REFERENCES

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TABLE 1

Single Well Analysis Parameters Held Constant, Wayne County, WV

| Parameter | Value |
|---|---|
| Gas Desorption Rate | 0.005 scf/psia/cu foot |
| Drainage Radius | 1,000 feet |
| Natural Fracture Spacing | 5 feet |
| Matrix Porosity | 0.01 (1 percent) |
| Matrix Permeability | 5 x $10^{-6}$ md |
| Fracture Porosity | 0.0009 (0.09 percent) |
| Permeability Anisotropy Ratio | 1:1 |
| Average Initial Rock Pressure | 375 psia |

TABLE 2

Parameters Determined by History Matching, Wayne County, WV

| Parameter | Range |
|---|---|
| Current Rock Pressure | 150-300 psia |
| Natural Fracture Permeability, $k_f$ | .02-.16 md |
| Net Producing Thickness, h | 40-310 feet |
| Flow Capacity, $k_f \cdot h$ | 1-42 md-feet |

TABLE 3

Single Well Analysis Parameters Held Constant, Meigs County, OH

| Parameter | Value |
|---|---|
| Gas Desorption Rate | 0.007 scf/psia/cu foot |
| Drainage Radius | 850 feet |
| Natural Fracture Spacing | 20 feet |
| Matrix Porosity | 0.02 (2 percent) |
| Matrix Permeability | 2 x $10^{-7}$ md |
| Fracture Porosity | 0.00078 (0.078 percent) |
| Permeability Anisotropy Ratio | 8.3:1 |
| Average Initial Rock Pressure | 680 psia |
| Net Producing Thickness | 56 feet |

TABLE 4

Parameters Determined by History Matching, Meigs County, OH

| Parameter | Range |
|---|---|
| Current Rock Pressure | 350-510 psia |
| Natural Fracture Permeability, $k_f$ | 0.04-0.5 md |
| Flow Capacity, $k_f \cdot h$ | 2-28 md-feet |

TABLE 5

Wayne County Reduced Study Area Data

| Well | Completion Date | Cumulative Production* (MMcf) |
|---|---|---|
| W1 | 1932 | 310 |
| W2 | 1941 | 382 |
| W3 | 1942 | 804 |
| W4 | 1955 | 1,370 |
| W5 | 1960 | 189 |
| W6 | 1965 | 24 |
| W7 | 1984 | 13 |

Field-Predicted Cumulative Production by Simulation = 3,098 MMcf.

Actual Field Cumulative Production = 3,092 MMcf.

* Values reported up to the end of 1985.

TABLE 6

20-Year Cumulative Production for Wayne County (MMcf)

| Well | Horizontal Shale Well | | | Vertical Shale Well | | | Improvement Ratio H:V |
|---|---|---|---|---|---|---|---|
| | Unstimulated | Stimulated | Interference | Unstimulated | Stimulated | Interference | |
| WHW1 | 820 | 1,659 | 187 | 78 | -- | 78 | 10:1 |
| WHW2 | 502 | 835 | 15 | 75 | -- | 3 | 7:1 |
| WHW3 | 149 | 589 | 70 | 22 | -- | 20 | 7:1 |

TABLE 7

Meigs County Reduced Study Area Data

| Well | Completion Date | Cumulative Production* (MMcf) |
|---|---|---|
| M1 | 1960 | 207 |
| M2 | 1947 | 301 |
| M3 | 1931 | 402 |
| M4 | 1960 | 375 |
| M5 | 1954 | 98 |

Field-Predicted Cumulative Production by Simulation = 1,390 MMcf.

Actual Field Cumulative Production = 1,383 MMcf.

* Values reported up to the end of 1986.

TABLE 8

Wayne County Horizontal Well Economic Analysis

| | 20 Years Gas Production (MMcf) | After Taxes Profit in 20 Years (1986 K$) | Required Drilling and Completion Costs (1986 K$) |
|---|---|---|---|
| Case No. 1 | | | |
| Gas Price = $2.00/Mcf<br>Payout Time = 3 Years<br>ROR = 20 Percent | 835 | 467 | 207 |
| Case No. 2 | | | |
| Gas Price = $2.00/Mcf<br>Payout Time = 5 Years<br>ROR = 20 Percent | 835 | 376 | 326 |
| Case No. 3 | | | |
| Gas Price = $3.50/Mcf<br>Payout Time = 3 Years<br>ROR = 20 Percent | 835 | 855 | 397 |
| Case No. 4 | | | |
| Gas Price = $3.50/Mcf<br>Payout Time = 5 Years<br>ROR = 20 Percent | 835 | 707 | 687 |

TABLE 9

Wayne County
2 Vertical Versus 1 Horizontal Well Economic Analysis

| Gas Price ($/Mcf) | After Tax Profit (K$) 2 Vertical | After Tax Profit (K$) 1 Horizontal | Payout Time (Years) 2 Vertical | Payout Time (Years) 1 Horizontal |
|---|---|---|---|---|
| 2. | - 78 | 157 | -- | 12 |
| 2.5 | - 14 | 333 | -- | 8 |
| 3. | 51 | 510 | 15 | 6.5 |
| 3.5 | 116 | 687 | 10.5 | 5.5 |
| 4. | 180 | 863 | 9 | 5 |
| 4.5 | 245 | 1,040 | 8 | 4.6 |
| 5. | 310 | 1,217 | 7.4 | 4 |
| 5.5 | 374 | 1,394 | 7 | 3.4 |
| 6. | 439 | 1,570 | 6.6 | 3 |
| 6.5 | 504 | 1,747 | 6 | 2.5 |
| 7. | 568 | 1,924 | 5.5 | 2.2 |
| 7.5 | 633 | 2,101 | 5.2 | 1.8 |
| 8. | 698 | 2,277 | 4.5 | 1.4 |
| 8.5 | 762 | 2,454 | 4 | 1.2 |

Assumed Drilling and Completion Costs

$133,000 -- Vertical Well

$657,000 -- 2,000 Foot Horizontal Well (includes vertical section)

TABLE 10

Meigs County Horizontal Well Economic Analysis

| | 20 Years Gas Production (MMcf) | After Taxes Profit in 20 Years (1986 K$) | Required Drilling and Completion Costs (1986 K$) |
|---|---|---|---|
| Case No. 1 | | | |
| Gas Price = $2.00/Mcf<br>Payout Time = 3 Years<br>ROR = 20 Percent | 571 | 282 | 44 |
| Case No. 2 | | | |
| Gas Price = $2.00/Mcf<br>Payout Time = 5 Years<br>ROR = 20 Percent | 571 | 253 | 90 |
| Case No. 3 | | | |
| Gas Price = $3.50/Mcf<br>Payout Time = 3 Years<br>ROR = 20 Percent | 571 | 606 | 108 |
| Case No. 4 | | | |
| Gas Price = $3.50/Mcf<br>Payout Time = 5 Years<br>ROR = 20 Percent | 571 | 540 | 225 |

TABLE 11

Meigs County
2 Vertical Versus 1 Horizontal Well Economic Analysis

| Gas Price ($/Mcf) | After Tax Profit (K$) 2 Vertical | After Tax Profit (K$) 1 Horizontal | Payout Time (Years) 2 Vertical | Payout Time (Years) 1 Horizontal |
|---|---|---|---|---|
| 2. | - 103 | - 38 | -- | -- |
| 2.5 | - 69 | 82 | -- | 17 |
| 3. | - 34 | 203 | -- | 13 |
| 3.5 | 0 | 324 | -- | 11.5 |
| 4. | 35 | 445 | 16.8 | 9 |
| 4.5 | 69 | 566 | 14 | 8 |
| 5. | 103 | 687 | 12.6 | 7.5 |
| 5.5 | 138 | 808 | 10.5 | 7 |
| 6. | 172 | 929 | 9.5 | 6.5 |
| 6.5 | 207 | 1,050 | 8.6 | 6 |
| 7. | 241 | 1,170 | 8 | 5.8 |
| 7.5 | 276 | 1,291 | 7.4 | 5 |
| 8. | 310 | 1,412 | 6.8 | 4.8 |
| 8.5 | 345 | 1,533 | 6.5 | 4.5 |

Assumed Drilling and Completion Costs

$133,000 -- Vertical Well

$657,000 -- 2,000 Foot Horizontal Well (includes vertical section)

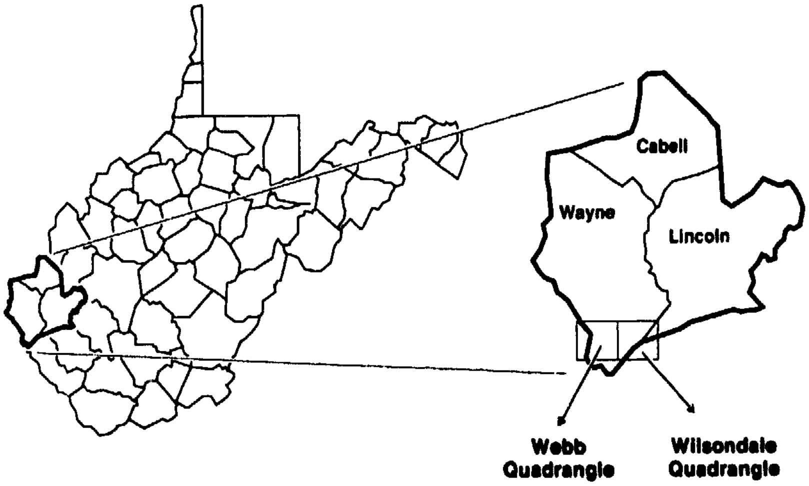



Fig. 1—Wayne County study area.

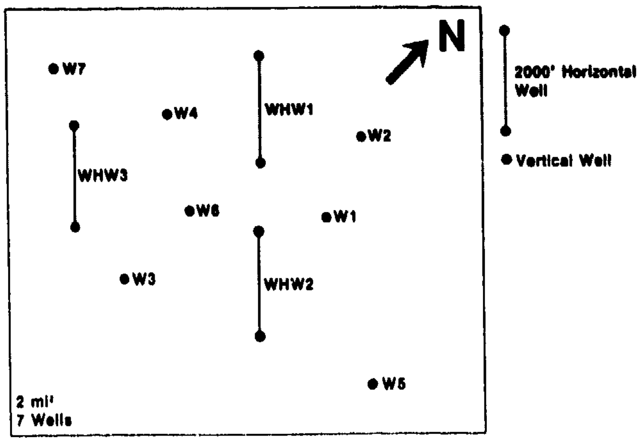



Fig. 2—Wayne County reduced site well location map.

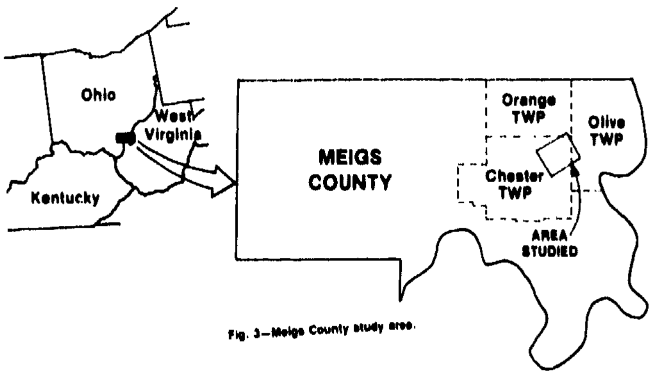



Fig. 3—Meigs County study area.

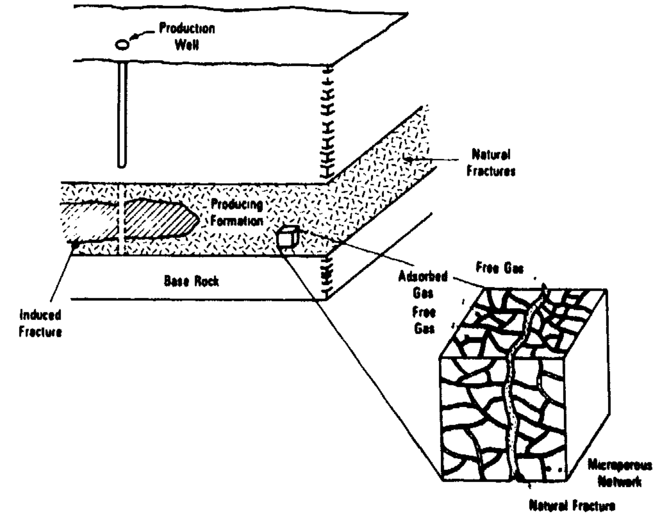
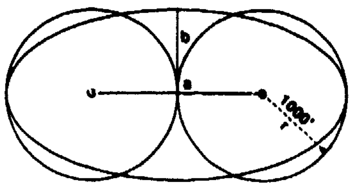



Fig. 4—Model depiction of shale gas storage and production.




Area of Circle $= \pi r^2 = \pi\,(1000)^2$

Area of Ellipse $= \pi ab = \pi\,(1000)\,(2000) = 2\pi\,(1000)^2$

20-Year Cumulative Production (MMCF)

| Wells | Unstimulated | Stimulated |
|---|---|---|
| 2 Vertical | 160 | 305 |
| 1 Horizontal | 502 | 835 |

Fig. 5—Drainage efficiency concept.

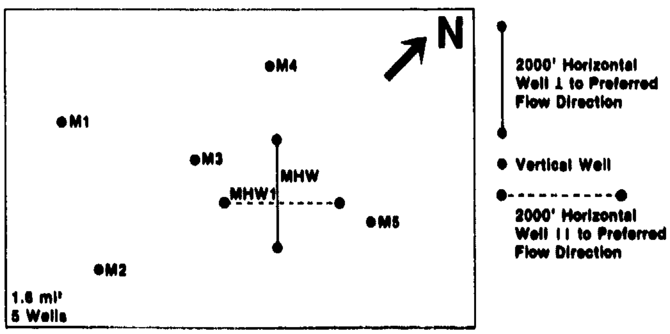



Fig. 6—Meigs County reduced site well location map.